LETTERS TO THE EDITOR

ASTROPHYSICS

Cosmic Ray Production by Vibrating Neutron Stars

I HAVE recently pointed out[1] that a vibrating neutron star, which is expected to be formed as a remnant of the explosion of a Type I supernova, may store up to 10^{51} or 10^{52} ergs as mechanical energy of vibration. This energy may be dissipated by various non-thermal mechanisms. If a magnetic field is embedded in the neutron star, then the vibrations will produce hydromagnetic waves which travel along the field lines, and these will be capable of accelerating charged particles to high energies by transit[2] and stochastic[3] acceleration processes. There is a possibility that the synchrotron radiation of X-rays from the Crab Nebula results from acceleration processes of this type, where the accelerated electrons have been able to diffuse into the outer expanding envelope. Such a diffusion is rendered easier if there should be a corona produced around the neutron star, which expands to form a stellar wind, thus drawing radially outward the magnetic lines of force. Such coronal heating may arise from shocks produced by the vibrations in the atmosphere[1] or by electromagnetic interaction between the magnetic field and the surrounding plasma (Manley, O., private communication).

If electrons can be accelerated to high energies in this way, then it should also be possible to accelerate ions in the vibrating magnetic field. This leads naturally to the hypothesis that vibrating neutron stars may be some of the principal injectors of high energy cosmic rays into the galaxy. Some aspects of this hypothesis are discussed in this communication.

The ions which would be accelerated to cosmic ray energies by vibrating neutron stars should certainly include those ions composing the corona. The corona should have the same composition as the photosphere of the neutron star, and if the corona is hot enough to expand in the form of a stellar wind, then the composition of the photosphere may change with time. Hence one test of this cosmic ray acceleration process is that the composition of the heavy cosmic ray primaries should be consistent with the changing abundances in the neutron star photosphere.

The abundances of cosmic ray primaries with $Z > 2$ are shown in Fig. 1. The abundances are based on measurements by Waddington[4,5] and by the Naval Research Laboratory group[6]. Also shown in Fig. 1 are the relative abundances of the elements with $Z > 2$ in the Sun and solar system. These abundances are based partly on solar spectroscopy[7], partly on meteorite analysis[7], and partly on rocket measurements of solar cosmic rays[8]. Both distributions are normalized to oxygen, and the abundances have been plotted as a function of mass number by spreading the abundances for each charge number over the principal isotopes of that element. Since the cosmic ray abundances have been strongly affected by spallation processes, this treatment produces a reasonably smooth abundance plot. The solar system abundances have been treated in the same way in order to facilitate comparison.

The differences between these two curves are striking. It appears that the cosmic ray abundance data cannot be obtained by accelerating particles with the relative abundances corresponding to solar composition, with modification by spallation, since there is a relative deficiency of cosmic ray nuclei in the vicinity of silicon and sulphur. On the other hand, it appears possible to account for the cosmic ray distribution if the products of three processes of nucleosynthesis form the material which is accelerated. These processes are:

(1) *Helium-burning.* Helium-burning thermonuclear reactions produce as products carbon-12 and oxygen-16. The relative abundances to be expected for these two products are unknown since these depend on the reduced α-particle width of the 7·12 MeV level of oxygen-16, which has not yet been measured.

(2) *Carbon-burning.* The products of the nuclear reactions of carbon-12 with itself are primarily neon-20, sodium-23 and magnesium-24. The relative abundances of these products which I found for a relatively slow process of carbon-burning[9] are shown near the bottom of Fig. 1. A significant abundance tail at higher mass numbers would be added if the carbon-burning occurred at somewhat higher temperatures, such as those in the supernova shock wave which traversed the outer layers of the supernova and ejected them into space.

(3) *The iron equilibrium peak.* When matter is heated to the vicinity of 3×10^9 °K or higher, the nuclei will rearrange themselves into the vicinity of the iron peak, where the binding energy per nucleon is a maximum. There is a distinct iron peak in the solar abundance data which shows the results of this process.

The heavy cosmic ray primaries appear to be composed principally of products of these three processes of nucleo-

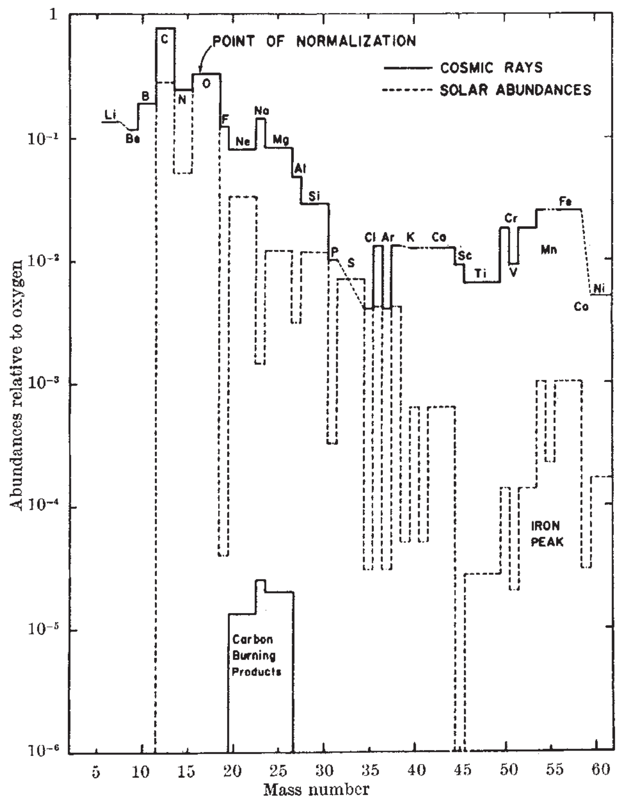

Fig. 1. Abundances in cosmic rays and in the solar system of elements with $Z > 2$. The heavier cosmic ray data are sparse, and some charges are missing. These gaps are bridged by dashed segments connecting the sections of the solid line. Shown near the bottom is the pattern of abundances formed in the carbon-burning process

synthesis, with subsequent modification by spallation. It appears that the nuclei have traversed about 3 or 4 g/cm^2 of material, presumably mostly hydrogen; but it is not clear how much of this matter was in the source and how much in the interstellar medium.

The evolution in the immediate presupernova stage of a star of not very great mass has been investigated by Chiu[10,11]. Following the process of helium-burning in the core, such stars become highly degenerate at their centres, and the emission of neutrino pairs prevents the temperature from rising rapidly until the mass of the core is near the Chandrasekhar limit, so that contraction becomes very rapid. Then carbon or oxygen burning will commence, but this will lead to an even stronger density concentration towards the centre. The supernova collapse is triggered when the high Fermi level of the electrons at the centre starts converting nuclei into neutrons.

Colgate and White[12] have shown that, during the collapse, a degenerate neutron core will be formed at the centre of the configuration. The material continuing to rain down on this core will produce very high temperatures and cause the formation of a shock wave. The shock wave will then traverse the outer layers, heating and ejecting them. Not all the material will be ejected to infinity; some of it will fall back and it is this material which we suspect will set up radial oscillations in the neutron star remnant.

In the interior of the neutron star ordinary nuclei will not exist. Near the surface, temperatures of 3×10^9 °K or higher will persist for times of 10^5 sec or longer. Under these conditions the material will be processed into the vicinity of the iron peak[13]. Nearer the surface the temperature will be insufficient for this to occur. Chiu and Salpeter[14] have shown that hydrogen and helium on the surface will be destroyed by inward diffusion, and that carbon will be destroyed to a considerable extent, but still heavier ions to a negligible extent.

Hence we see that even if the layer initially composing the neutron star surface contains only light elements, the final layer is likely to contain carbon, oxygen, carbon-burning products, and the iron peak. The high density at which helium-burning would occur in the surface will favour the formation of carbon relative to oxygen, as is observed in the cosmic rays. Because the temperature will fall rapidly in the envelope beyond the thermal conduction central plateau, the intermediate stage consisting of silicon and sulphur will have only small abundances, and this region will not be built up by nuclear reactions accompanying diffusion.

Thus we see that if the outer layers of the neutron star are peeled off by a stellar wind, the corona is likely to be initially composed of carbon and oxygen, later of the products of carbon-burning, and eventually of iron peak nuclei. Hence the neutron star cosmic ray acceleration hypothesis seems not inconsistent with our knowledge of the structure of a neutron star and of the processes of nucleosynthesis.

The bulk of the cosmic rays consists, not of nuclei with $Z > 2$, but of protons and α-particles. It is evident that under the conditions described here these could not be accelerated in the immediate vicinity of a neutron star. However, in the present picture in which the neutron star has a stellar wind which draws the magnetic field out in the radial direction, hydromagnetic waves may be able to progress from the vicinity of the neutron star out into the expanding ejected envelope. Such a model would seem appropriate for the Crab Nebula, and the hydromagnetic waves would then have an opportunity to accelerate protons and α-particles in the envelope. But protons and α-particles would also be the principal products accelerated in the supernova hydrodynamic hypothesis of Colgate and Johnson[15].

For many years supernova remnants have seemed likely sources for the acceleration of cosmic rays. Arguments toward this end have been based on the obvious availability of large amounts of energy and of the presence of energetic particles as revealed by synchrotron emission. However, specific models for the acceleration process have been lacking. It is hoped that the present model will serve as a basis for further quantitative investigations.

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GEOPHYSICS

Determination of the Mean Residence Time in the Troposphere by Measurement of the Ratio between the Concentrations of Lead-210 and Polonium-210

IT has been pointed out by several authors that the concentration of polonium-210 (radium-F) in rain water is lower than that which would result from the radioactive equilibrium between lead-210 (radium-D) and polonium-210 (radium-F)[1,2] (the decay chain, it should be remembered, is:

$$\underset{222}{\text{radon}} \xrightarrow{3\cdot8} \text{radium-A,B,}\ldots\text{C}'' \longrightarrow \underset{(\text{lead-210})}{\text{radium-D}} \xrightarrow{20\text{y}}$$

$$\underset{(\text{bismuth-210})}{\text{radium-E}} \xrightarrow{5\text{d}} \underset{(\text{polonium-210})}{\text{radium-F}} \xrightarrow{138\text{d}} \underset{206}{\text{lead}}$$

This lack of equilibrium has been ascribed to the washing of the radioactive aerosols present in the troposphere by rain. For two successive products of the decay chain, in equilibrium at the origin, this washing requires a change in the traditional equation:

$$\lambda_1 N_1 = \lambda_2 N_2 \qquad (1)$$

to:

$$\lambda_1 N_1 = (\lambda_2 + \lambda) N_2 \qquad (2)$$

where N_1 and N_2 are the concentrations of two nuclides having constants λ_1 and λ_2, and $\lambda = 1/\tau$, a constant equal to the inverse of the mean residence time in the troposphere.

Measurement of the ratios of radium-D and radium-F activities in rain water enables us to compute this time τ. In this case, the formula is:

$$\frac{\lambda_F}{\lambda_D}\frac{N_F}{N_D} = \frac{\lambda_E\ \lambda_F}{(\lambda_E + \lambda)\ (\lambda_F + \lambda)} \qquad (3)$$

In fact, Burton and Stewart[1] showed that an important part of radium-D is produced directly in the troposphere by the disintegration of the radon and of its decay products. As the mean residence time in the troposphere (measured by various ways) is found to be about 30 days, the equilibrium between radium-D and -E may practically be achieved there, but this is not so for radium-F. In those conditions, equations (2) and (3) are valid only for